Thermoregulatory Models of Space Shuttle and Space Station Activities

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Background: Thermoregulation is critical for survival in space, especially during contingencies demanding of human cognitive and physical performance. A review of the negative feedback human thermoregulatory system is provided. The Advanced Crew Escape Suit is worn by astronauts during ascent and descent on the Space Shuttle to provide active cooling for nominal and contingency operations and protection from loss of cabin pressure mishaps. Failure of a thermal system control element during a recent Shuttle flight resulted in a single point failure that could have elevated cabin temperature, possibly resulting in cognitive deficits of the pilot during the reentry and landing phases. ***Methods:*** The efficacy of the existing cooling equipment and procedures for maintaining crew thermal comfort in the event of such a failure was assessed. The Wissler and 41-node thermoregulatory models were used to conduct a parametric study of Shuttle cabin temperatures and resulting thermal effects on crew. ***Results:*** Under high metabolic loads, crewmember core temperatures and heat storage are shown to increase beyond allowable limits using this analysis. Resulting levels of thermal stress may exceed standardized limits, after which cognitive performance and manual tracking ability are diminished. ***Discussion:*** The operational procedure for entry and landing during this failure scenario may result in significant thermal compromise to crewmembers, including cognitive and manual performance deficits. Revision of the flight rule governing crew actions during compromise of cabin thermal control has been undertaken to minimize thermal stress on returning Shuttle crewmembers. Modifications to the crew thermal protection system for the Shuttle are suggested.

Keywords: space physiology, thermoregulation, modeling, Shuttle, Space Station, astronauts, ACES.

FOR HUMANS TO EXIST in a hostile environment such as space, it is necessary to provide sophisticated support systems to emulate the Earth's environment. First, it is necessary to maintain a non-toxic environment with a partial pressure of oxygen between 120 and 280 mmHg that brackets the sea level partial pressure of oxygen of 160 mmHg. This range represents a zone of unimpaired human performance, since hypoxia occurs below a partial pressure of 120 mmHg and hyperoxia at a partial pressure greater than 280 mmHg of oxygen. Second, it is important to assure that astronauts do not undergo a rapid reduction in pressure that would cause decompression sickness (DCS) if their atmosphere contains an inert gas such as nitrogen, which is eliminated slowly from tissue. Both the Shuttle and the International Space Station (ISS) have atmospheres approximating normal sea level pressure, with 20% oxygen and 80% nitrogen. In each case, the space suits used to carry out extravehicular activities (EVA) have an atmosphere of 100% oxygen at 222 mmHg (4.3 psia). To avoid DCS, NASA currently uses various oxygen pre-breathe protocols, which may involve intermediate pressure stages and exercise prior to EVA. Third, and the focus of this paper, is the need to maintain an acceptable thermal environment for astronauts as they carry out dynamic flight activities. The thermal state of astronauts is of special interest when they are in an EVA suit or the Shuttle Advanced Crew Escape Suit (ACES), which is worn during launch and landing and designed to protect crewmembers in event of loss of spacecraft pressure and to maintain body temperature when the astronaut may be under significant metabolic or external thermal loading.

The STS-111 Endeavor Space Shuttle mission had the responsibility to return experimental test equipment from the ISS in the habitable atmosphere that required continuous power. This produced an increased cabin thermal load during reentry. Two days into the flight, one of Endeavor's Flash Evaporator System controllers failed. The Flash Evaporator System provides cooling to the Shuttle cabin during launch and entry by utilizing the phase change of water exposed to a vacuum. Fortunately, the system's back-up controllers continued to function normally, with no effect on mission operations. It did, however, prompt consideration of corrective actions to be taken if both controllers had degraded. Such failures would have resulted in elevated cabin temperatures during entry, which would have reduced the effectiveness of the liquid cooling and ventilation garment (LCVG) worn under the ACES. Such a decrement, and its concurrent effect on astronaut performance,

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may have occurred in the phase of reentry involving piloted control inputs during manual landing.

To investigate the effect of such a failure, two mathematical models of human thermoregulation were employed, the 225-node Wissler model and the 41 Node Metabolic Man model. These models have a rich legacy of space mission support, dating back to the Apollo Program when the 41 Node Metabolic Man model was used for real-time management of Extravehicular Mobility Unit (EMU) consumables, astronaut thermal comfort and heat storage, and traverse objectives during EVA on the lunar surface (5,12). For this study, both the 41 Node Metabolic Man model (4,5) and the Wissler model were modified and adapted for a personal computer (13–15). After correlating them with data from related extreme environment studies, they were used to evaluate the ACES/LCVG system and propose solutions to the marginal performance characteristics that were predicted. A review of human thermal regulation is offered to provide context for the ACES modeling study.

Human Thermal Regulation

Humans are classified as *homeotherms*, organisms that have nearly constant body temperature that is largely independent of the temperature of their surroundings. Human oral body temperature is 37°C with a diurnal variation of about 0.5–0.8°C. Lower values occur in the early morning and higher values in the late afternoon. Rectal core temperatures are slightly higher than oral temperatures with an average of 37.5°C and exhibit similar diurnal variation. Exertion that increases the metabolic rate increases core temperature. Major factors affecting human thermal regulation in a gaseous environment include the environment, the individual's physiological state, the clothing, and the particular functions being carried out and the time of day; see Reeves (11) for more detail.

Thermoregulation is the process by which the body maintains its nominal core temperature given changes in external temperature and metabolic loading. Increases or decreases in metabolic rate respectively increase or decrease the production of heat. Factors that affect the metabolic rate include exercise, hormone levels, stress, ingestion of food, age, and gender. Heat is transferred from the environment to the surface of the body and lungs by radiation, evaporation, conduction, and convection. Thus, the balance between heat production and loss is derived from the first law of thermodynamics:

$$\dot{Q}_m = \dot{Q}_e + \dot{Q}_r + \dot{Q}_k + \dot{Q}_c + \dot{Q}_{st} + W \qquad \text{Eq. 1}$$

where:

$\dot{Q}_m$ = metabolic heat rate
$\dot{Q}_e$ = evaporative heat loss positive, gain negative
$\dot{Q}_r$ = radiative heat loss positive, gain negative
$\dot{Q}_k$ = conductive heat loss positive, gain negative
$\dot{Q}_c$ = convective heat loss positive, gain negative
$\dot{Q}_{st}$ = heat storage rate
W = mechanical work rate

Body temperature is controlled by negative feedback that requires sensors, a controller, and actuators. In addition to the hypothalamus itself that also acts as a sensor, cold and warm sensitive temperature receptors are located throughout the body. The body temperature receptors are located in the skin and in the interior of the body, specifically in the spinal cord, abdomen, larger veins, and thorax. The hypothalamus, primarily neurons in the anterior hypothalamic-preoptic region, is generally recognized as the body's temperature controller or thermostat. The hypothalamic thermostat works in conjunction with other hypothalamic, autonomic, and higher nervous thermoregulatory centers to keep core body temperature constant. Temperature-sensitive neurons in the hypothalamus are stimulated by the temperature receptors: warmth-sensitive neurons increase their firing rate in response to an increase in body temperature to promote heat loss; cold-sensitive neurons increase their firing rate in response to a decrease in body temperature to promote heat conservation and increase heat production. Additional thermoregulatory responses are involuntary, mediated by the autonomic nervous system and neurohormonal pathways, while others involve semi-voluntary or voluntary behavioral activity.

Heat conserving responses: If the core body temperature decreases below the set point, cold sensitive neurons, primarily in the anterior hypothalamic-preoptic region, initiate the following heat conserving responses:

1) Cutaneous vasoconstriction—Stimulation from the posterior hypothalamic-preoptic sympathetic centers constricts smooth muscles in the arterioles near the body's surface. As a result, warm blood is moved deeper within the body so that heat loss is reduced. Maximal vasoconstriction can decrease cutaneous blood flow to 30 ml · min^{-1} from a nominal flow of 300–500 ml · min^{-1}.
2) Piloerection—Piloerection as a response to cold is vestigial in humans. Since humans retain very little body hair, the reflex does not serve a useful purpose. The sympathetic nervous system causes small muscles at the base of each hair, the arrectores pilorum, to contract and pull the hair erect, resulting in goose bumps in humans. While not important for humans, piloerection in animals allows the entrapment of a thicker layer of insulated air to reduce heat transfer.
3) Chemical thermogenesis—Production of thyrotropin releasing hormone stimulates the anterior pituitary gland to increase secretion of thyroid stimulating hormone that in turn promotes production of thyroxin (T4) by the thyroid; the resulting T4-induced increase in cellular metabolism produces heat. In addition, an increase in sympathetic stimulation and release of epinephrine and norepinephrine from the adrenal medulla also increases cellular metabolism.
4) Shivering—The primary shivering motor center, located in the dorsomedial region of the posterior hypothalamus, is stimulated by signals from the cold-sensitive receptors in the skin and spinal cord. When activated, the shivering motor center transmits signals to the anterior motor neurons that increase the tone of the skeletal muscles.

When the tone increases above a critical level, shivering is initiated. Shivering can increase surface heat production by 500%. However, this effect is limited to a few hours because of depletion of muscle glycogen and the onset of fatigue.

Hypothalamic responses: If the core body temperature increases above the set point, the warmth-sensitive neurons, primarily in the anterior hypothalamic-preoptic region, initiate the following hypothalamic responses:

1) Cutaneous vasodilation—Inhibition of the adrenergic activity of the sympathetic centers in the posterior hypothalamus causes the smooth muscles of the arterioles to relax, resulting in dilation of blood vessels in the skin. This increases skin blood flow and therefore temperature, promoting heat transfer out of the body. Maximal vasodilation can increase cutaneous blood flow to 3000 ml $\cdot$ min^{-1} from a nominal flow of 300–500 ml $\cdot$ min^{-1}.
2) Decrease in metabolic rate—Reduction in the metabolic rate decreases the production of heat by the body. This is realized by inhibiting the mechanisms that produce heat by chemical thermogenesis and shivering as discussed above.
3) Sweating—If the body's heat is sufficiently high, the cholinergic sympathetic fibers that innervate the sweat glands release acetylcholine, which stimulates sweat. This activation of the sweat glands produces sweat that results in heat loss through evaporation. By this mechanism, many times the basal metabolic heat rate can be removed.

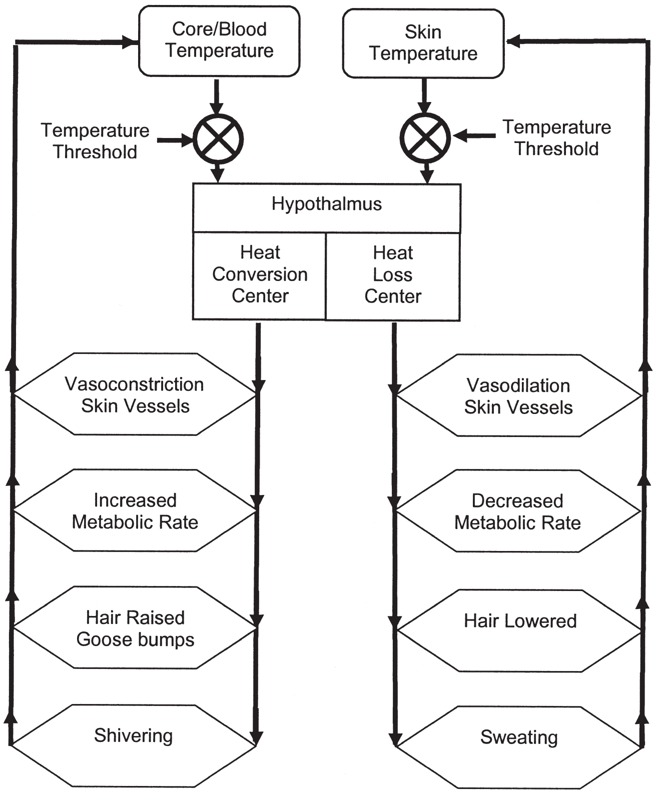

Fig. 1. Thermoregulation feedback control.

A schematic of the thermoregulatory system is illustrated in **Fig. 1**.

The body's ability to maintain core and skin temperature in changing environments is critical to survival. However, if the external and/or metabolic factors are extreme, the body cannot compensate and significant deficits will occur as identified in **Table I**.

Both hypothermia and hyperthermia result in the impairment of normal cerebral and motor functions. The comfortability of a range of mean skin temperatures is given in **Table II**.

Small increases in body core temperature can impair the ability to carry out complex tasks. Increases in body temperature will adversely affect short-term memory and slow perceptual and motor skills. If the temperature increases to 38.3°C (101°F), for example, an aviator's error rate will roughly double (1). Heat storage is a measure of the heat content of the human body. It is directly proportional to the rise in body core temperature above its normal set point of 37°C and skin temperatures above their normal set point of 33°C. For more details on heat storage computation and significance, see Kuznetz (5).

Description of ACES

Following the loss of the Shuttle Challenger during an ascent mishap, full pressure Launch and Entry Suits replaced the fabric flight suits. During reentry, Shuttle astronauts also wear anti-gravity pressure bladders on the legs and abdomen to resist pooling of blood in the lower body. The reduction of plasma volume resulting from microgravity adaptation can lead to reduced cognitive and motor function due to a lack of cerebral perfusion during the $+G_z$ acceleration forces imposed during reentry. However, this also imparts additional thermal stress, which due to vasodilatation may exacerbate orthostatic intolerance. This prompted the addition of an active crew cooling system into the next generation of pressure suit. The resulting ACES and its integrated LCVG provide temperature regulation to crewmembers during launch and entry operations of the Space Shuttle by providing circulating cooling water from the Individual Cooling Units (ICUs) located in the flight deck. The ACES is designed to protect the Shuttle crew in the event of loss of cabin pressure up to an altitude of 30 km and to insulate the crew from cold air and cold water if they need to bail out in an emergency. Use of the ACES and LCVG is associated with subjectively greater comfort and decreased heart rates during entry (10), suggesting effective cardiovascular protection.

Shuttle Thermal Control Systems

Thermal control in the Shuttle is provided by the Water Coolant Loop System that removes heat from a variety of air and water heat exchangers and returns cold air or water as appropriate. The water loop in turn transfers heat loads to external circulating freon loops, which flow to radiators in the open payload bay doors where heat is rejected to space while the Shuttle is in orbit. Otherwise, during ascent and descent when the

TABLE I. CORE TEMPERATURES EFFECTS.

Condition	Temperatures (°C)	Symptoms
Heat Stroke	> 44	Brain death certain
	41–44	Includes all systems of heat exhaustion plus dysfunction of central nervous system causing altered mental state, disorientation, strong rapid pulse, coma, and beginning of brain death
Heat Exhaustion	39–41	Fatigue and weakness, nausea and vomiting, headache, muscle cramps, irritability, pulse raised
Heat Cramps	39-38	Painful muscle spasms with pulse normal or slightly elevated, often caused by salt depletion
Normal	38-36	Normal
Mild Hypothermia	36-35	Cold sensation, goose bumps, lack of some hand coordination, shiver can be mild to severe
Moderate Hypothermia	35-34	Intense shivering, apparent lack of muscle coordination, movements labored, mild confusion but appears alert
	34-32	Violent shivering, difficulty speaking, lack of some cognitive functions, muscle stiffness, sign of depression
Severe Hypothermia	32-30	Shivering stops, incoherence, poor muscle coordination, irrational and confused, inability to walk,
	30-28	Muscle rigidity, semi-consciousness, pulse and respiration decrease, pupil dilation, desire to sleep, possible heart fibrillation
	28-26	Unconscious, muscle failure, pulse and heart rate erratic, respiratory failure, possible death
	< 26	Pulmonary edema, cardiac and respiratory failure, death

bay doors are closed, a flash evaporator system is utilized. This system removes heat by spraying water against the inside surface of a rotating drum exposed to a vacuum. The resulting "flash evaporation" of water provides cooling to the freon loops embedded in the drum by the phase change of water as it evaporates. The system provides a cooling capability of 1,040 BTU · lb^{-1} of evaporated water. Below an altitude of 30.5 km (100,000 ft) the flash evaporator system can no longer provide sufficient cooling and heat rejection is then augmented by an ammonia boiler system until after landing, when ground support personnel attach the ground support heat exchanger. The cooling water in the LCVG of each astronaut exchanges heat with the cabin atmosphere by means of the thermal electric ICUs, which are under individual astronaut control. Often two astronauts are on the same ICU. Consequently, if the cabin temperature is elevated, the inlet temperature of the cooling water in the LCVG will be elevated.

The thermal pathways for the astronaut in the ACES are illustrated in **Fig. 2**, where the atmosphere in the ACES is the private atmosphere.

TABLE II. SKIN TEMPERATURE COMFORTABILITY.

Local Skin Temperature (°C)	Degree of Comfort
> 36	Uncomfortable
34–36	Slightly uncomfortable
34-32	Comfortable
32-30	Slightly uncomfortable
< 30	Uncomfortable

Effects of Elevated Temperature with the ACES

Fig. 3 illustrates the comfort zone for test subjects wearing the LCVG and ACES derived from tests in which the subjects performed various tasks at different workloads and environments (5). The comfort zone is determined primarily by skin temperature. The upper, or warm, limit corresponds to the threshold at which the subjects began to feel uncomfortable because of the inability of the LCVG to remove excess heat due to an elevated inlet coolant temperature. The lower, or cool, limit corresponds to the threshold at which the subjects began to feel uncomfortable because of the removal of heat by the LCVG with a low inlet coolant temperature. This comfort band is frequently used by NASA as a safety envelope for various tasks in extreme temperature environments such as for the ACES/LCVG suited

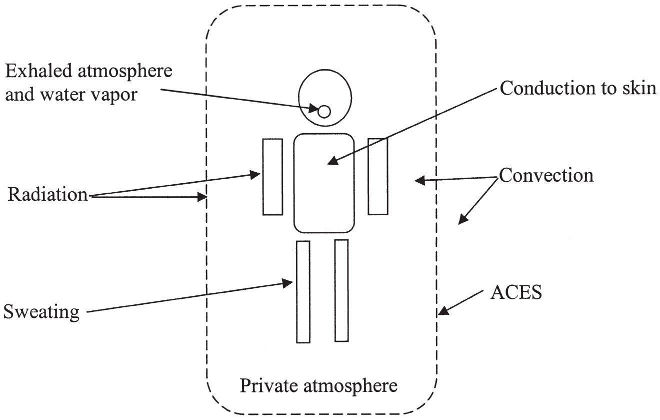

Fig. 2. Advanced Crew Escape Suit (ACES) thermal pathways.

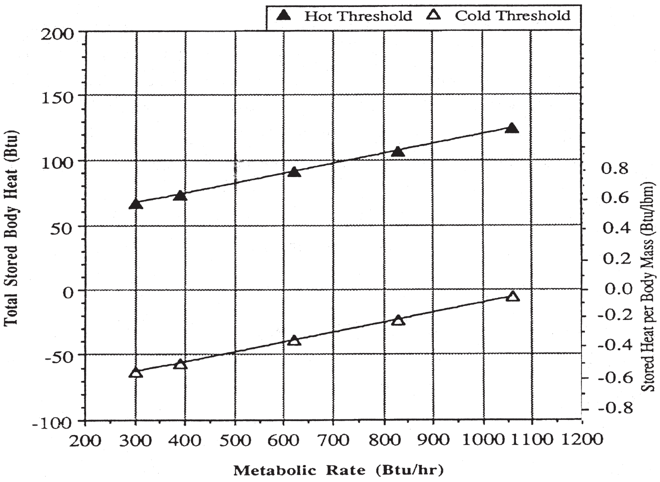

Fig. 3. Comfort zone for Advanced Crew Escape Suit (ACES) suited subjects [from Kuznetz (5)].

subjects. It shows that a deviation in stored heat from comfort of ±16 kcal (±62 BTU) crosses the hot and cold thresholds at a nominal metabolic rate of 300 BTU · h^{-1}.

Mathematical Models of Thermoregulation

Human body thermoregulatory simulators are generally modeled as controlled or passive systems being regulated by a controlling or active system. The passive system consists of multiple layers of tissue representing the core, muscle, fat, and skin, while the active system simulates functional differences in the body's neural control system. In the passive system, skin layers exchange heat with the environment by conduction, convection, evaporation, and radiation, while in the active system, signals proportional to temperature deviations from "set points" in the skin and hypothalamus are sensed by a detector (the neural system), modified by an integrator (the brain), and used as commands by effectors (the sweat glands, muscles, and cardiovascular system). In this approach, commands influencing mechanisms such as sweating, shivering, and blood flow regulation are used to keep the body temperature constant and maintain homeostasis.

Because of the complexity of the human thermoregulatory system, contributing components should be taken into account comprehensively in modeling. These include: 1) environment—atmospheric constituents, pressure, temperature, humidity, and flow rate; 2) clothing—thermal conductivity and permeability; 3) anatomical characteristics—surface area, mass, body composition, heat capacity, gender, and age; 4) activity—workload, metabolism, oxygen uptake, respiratory heat loss, and acclimation; and 5) physiological response—shivering, sweating, vasoconstriction, vasodilation, blood flow rate, and heart rate.

The thermoregulatory models used here, the Wissler model and the 41 Node Metabolic Man, were developed respectively by Eugene H. Wissler (13–15) and Lawrence H. Kuznetz (4). These models were modified to simulate an automatic control system for a liquid cooling garment to provide thermal comfort to astronauts and cover a broad range of human experiences from immersion in cold water to exercise in a hot humid environment (5,6,8,9,16). Human thermal characteristics may be described and modeled in terms of elements and nodes. Elements are the number of major body segments considered in a model such as a head, torso, arms, legs, feet, and so on. Nodes are mathematically defined subsegments of constant temperature within each element, such as concentric cylinders of core muscle, fat, and skin within a torso.

The Wissler model utilizes a 15-element representation of the human body with 15 nodes in each element for a total of 225 nodes and has been validated with the performance of divers working as deep as 450 m and with subjects up to altitudes of 9000 m. The 41 Node Metabolic Man model has 10 elements with 4 nodes in each for a total of 41 nodes, and has been validated for astronauts in thermal chambers wearing spacesuits in extreme environments. Each model uses concentric cylinders to simulate muscle, fat, bone, and skin, and has a vascular system composed of arteries, veins, and capillaries. Physical properties and physiological variables (such as temperature, metabolic and perfusion rates, oxygen and carbon dioxide tensions, and lactate concentrations) are described as functions of polar coordinates and time. Algorithms are used to represent the thermoregulatory and cardiovascular responses. The heat transfer equations and material balances for oxygen, carbon dioxide, and lactate are evaluated by finite–difference methods.

Model Validation

To assure that the human body thermoregulatory simulations were functioning properly, a series of verification checks was made. These included quantitative comparisons with the results of simulations from prior implementations that compared with rounding errors, checking the conversion of selected inputs with internally computed parameters to assure that the inputs were being properly interpreted, and qualitative assessments of the output to changes in the inputs. Two other validation tests were also carried out with data obtained from human subjects. The first validation utilized data provided by Hagan and obtained at the Naval Medical Research and Development Command (3). This data set was of fully outfitted firefighters whose rectal and mean skin temperatures were recorded during exercise in moderate, warm, and hot air environments at high metabolic rates. Good agreement was obtained between the simulations and the measured core and mean skin temperatures. The second validation compared predictions with the results of a human subject test aimed at determining if the ACES and the LCVG could protect against a simulated Shuttle reentry temperature profile higher than currently allowed by NASA flight rules (Lee SMC, McDaniel A, Jacobs T, Schneider SM. Performance of the individual cooling unit and liquid cooling and ventilation garment sys-

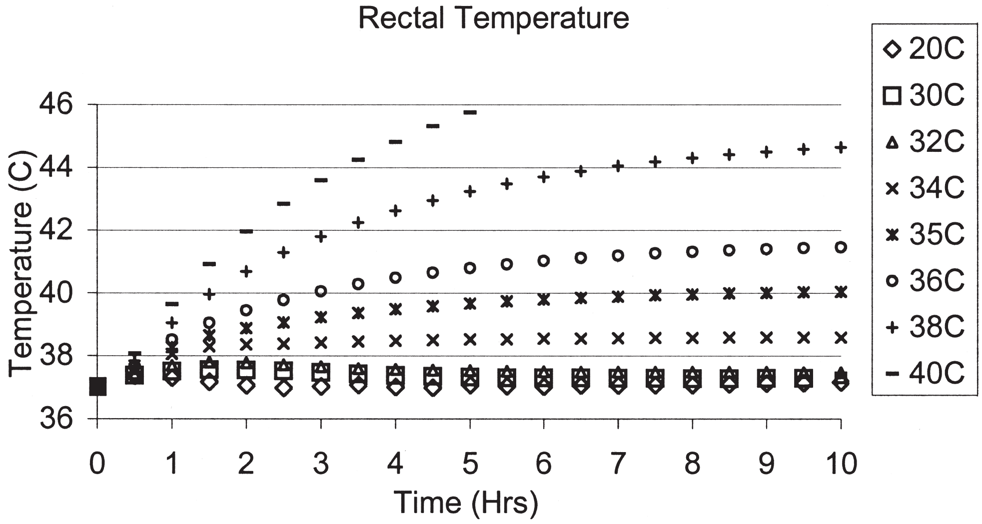

Fig. 4. Rectal temperatures as function of time for parametric cabin temperatures; metabolic rate is 151 kcal · h^{-1} (600 BTU · h^{-1}).

tem at elevated cabin temperatures. Personal Communication; 2002). Eight subjects (four men and four women) wearing the ACES and the LCVG were placed for 5 h in a chamber in which the temperature, humidity, and inlet water coolant temperature were increased and the water flow rate was under control of the subjects. Good agreement was obtained for rectal temperature, mean skin temperature, and water outlet temperature.

Shuttle Parametric Study

The Wissler and 41 Node Man models were modified and configured to carry out a parametric study of astronauts clothed in the LCVG/ACES ensemble under the conditions of a degraded thermal control system such as occurred on Endeavor. The simulated astronaut had the following properties:

1) Subject:
   Mass = 72.7 kg (160 lbs)
   Mean Skinfold Thickness = 10 mm
   Position = seated
2) Subject Metabolic Rate:
   Resting = 113.4 kcal · h^{-1} (450 BTU · h^{-1})
   Incremental component varied from 37.8 kcal · h^{-1} (150 BTU · h^{-1}) to 630.0 kcal · h^{-1} (2500 BTU · h^{-1}) 15% was assigned each to the muscles in the legs and arms and 35% each to the muscles in the lower and upper trunks
3) Environmental Conditions:
   Pressure = 1 atm
   Dry-bulb Temperature = varied
   Black Globe Temperature = dry-bulb temperature
   Dew-point temperature was varied so relative humidity was 50%
   Breathing = air at cabin temperature
4) LCVG:
   Coolant flow rate = 36.4 kg · h^{-1} (80 lb · h^{-1}) (maximum possible)
   Coolant inlet temperature = cabin dry-bulb temperature (−2°C)

Figs. 4 and 5 are the Wissler model's predictions of rectal and mean skin temperature vs. time for a constant metabolic rate of 151.2 kcal · h^{-1} (600 BTU · h^{-1}) as cabin temperatures increase. **Fig. 6**, by contrast, expresses steady state predictions of rectal temperature as a function of metabolic rate as cabin temperatures in-

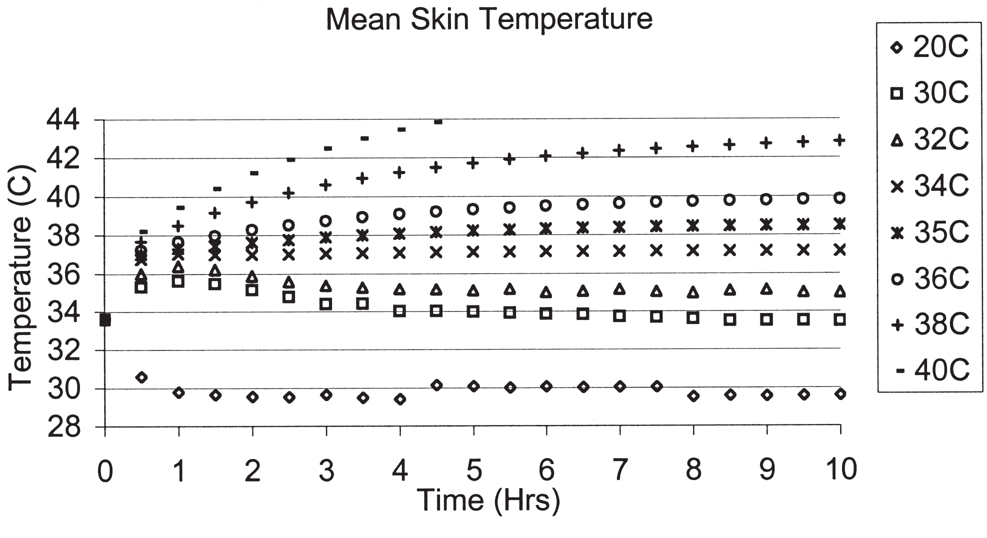

Fig. 5. Mean skin temperatures for parametric cabin temperatures; metabolic rate is 151 kcal · h^{-1} (600 BTU · h^{-1}).

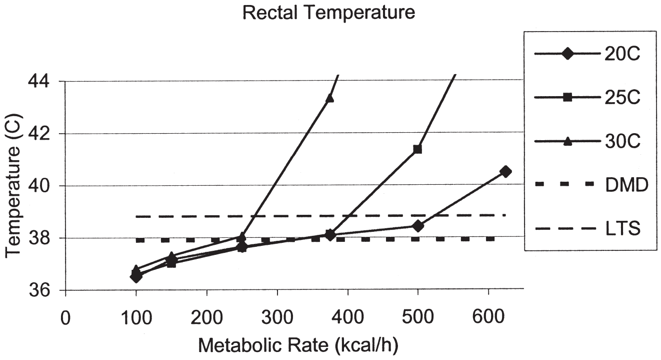

Fig. 6. Steady-state rectal temperatures vs. metabolic rate for parametric cabin temperatures. DMD = Decreasing Manual Dexterity (37.9°C) (3); LOTS = Loss of Tracking Skills (38.8°C) (2); Upper limit of interest LCVG upper steady-state design limit = 403 kcal · h^{-1}.

crease. The range of 300 to 400 kcal · h^{-1} (1200–1600 BTU · h^{-1}) in Fig. 6 encompasses the upper limit of sustained metabolic rate for a fighter pilot at 300 kcal · h^{-1} (1200 BTU · h^{-1}) (Clark J. Fighter pilot heat load. Personal communication; 2003), and for an EVA at 400 kcal · h^{-1} (1600 BTU · h^{-1}). Based on Fig. 6, relatively high metabolic rates such as these are sustainable only as long as cabin temperatures are kept below 20°C. If, on the other hand, increases in cabin temperature caused by the type of failure analyzed in this study exceed this boundary, severe compromises in crew judgment, motor skills, and landing/entry performance can result. The Cognitive Deficit Onset (CDO), Decreasing Manual Dexterity (DMD), and Loss of Tracking Skills (LOTS) are standard thresholds of human performance decrements due to thermal stress on humans (2). Fig. 6 graphically expresses the rise in core temperature obtained in this analysis against these thresholds. The CDO, DMD, and LOTS redlines were determined by combining the relationship between thermal stress and crew performance expressed in Tables I and II into the combined redline limits of **Table III**. In addition to rectal or core temperature limits, Table III also relates the more frequently utilized heat storage limits to human performance decrements. A heat storage level of 300–400 BTUs, for example, or a rectal temperature of 37.7–38.2°C, is now expressed as a redline equivalent to the first observed decrements in cognitive tasks or manual dexterity (DMD or CDO). Likewise, increases of heat storage and core temperature to more serious levels of risk and possible heat exhaustion, occurring at 400–600 BTUs or 38.2–39.2°C, are now manifested as tracking skills deficits at the LOTS threshold. Superimposing these DMD, CDO, or LOTS redlines against the results of Fig. 6 or similar figures transforms the Wissler and 41 Node Man models from heat storage or rectal temperature simulators to forecasters of performance decrement, a tool more easily appreciated as an index of risk.

TABLE III. HUMAN THERMAL REGULATORY LIMITS.

Rectal Temperature Limits (°C)	Equivalent Heat Storage (BTU)	Medical Conditions
37.7–38.2	300–400	Cognitive tasks decrement onset Decreasing manual dexterity Discomfort (NIOSH limit) Hyperthermia/Heat Stress
38.2–39.2	400–600	Slowed cognitive function Increased errors in judgment Loss of tracking skills 25% risk of heat casualties Possible heat exhaustion
39.2–39.6	600–800	Functional limit of physical tasks 50% risk of heat casualties Probable heat exhaustion Possible heat stroke
> 40	> 800	100% risk of heat casualties Probable heat stroke

By way of example, the results of Fig. 6, combined with Table III, illustrate that these DMD and CDO limits are approached at a 25°C cabin temperature as metabolic rates rise above 200 kcal · h^{-1} (600 BTU · h^{-1}). Similar simulations performed with the 41 Node Man model show that the LCVG as presently configured is wholly inadequate at cabin temperatures above 35°C. These results and other parametric studies were used to produce **Table IV** (7), an estimate of the CDO and LOTS limits for a range of hot cabin reentry scenarios. Table IV was eventually embodied in the form of a formal NASA flight rule (A13–151, Hot Cabin Atmosphere) for the hot cabin reentry scenario.

Conclusions

Thermoregulatory models, such as the Wissler and 41 Node Metabolic Man models, are versatile tools that can determine the heat distribution and risk for an individual under a variety of conditions, including astronauts wearing the ACES and LCVG. For the Shuttle, if the cabin temperature rises above 25°C and the metabolic rate increases above 200 kcal · h^{-1} (600 BTU · h^{-1}), the critical performance parameters of rectal temperature and stored heat approach the DMD and CDO limits. At the upper limit metabolic rates of 300–400 kcal · h^{-1} (1200–1600 BTU · h^{-1}) the LCVG as configured is predicted to be inadequate. Prior studies (6; and Lee SMC, McDaniel A, Jacobs T, Schneider SM. Personal communication, 2002) have shown that the robustness of the system can be greatly improved by providing lower LCVG inlet coolant temperatures. Feasibility studies at the Johnson Space Center are underway to investigate the cost of implementing this improvement. This would result in an increased margin against incurring performance impairments. The conclusions of this study were instrumental in changing an existing NASA Flight Rule (A13–151) that had required wearing the ACES in a hot cabin reentry with a failed flash evaporator or cabin fan. The revised flight rule, based on this analysis, requires the ACES to be removed and the crew to be in shirtsleeves if the cabin temperature exceeds 35°C (95°F) prior to reentry.

TABLE IV. NASA FLIGHT RULES A13-151 HOT CABIN ATMOSPHERE (10).

	Temperature				
	70 °F 21.1 °C	80 °F 26.7 °C	90 °F 32.2 °C	95 °F 35.0 °C	100 °F 37.8 °C
Time to CDO with ACES off	≫3 h	≫3 h	3.25 h	2.45 h extrapolated	1.66 h
Time to CDO with ACES on	≫3 h	≫3 h	1.25 h	0.75 h extrapolated	0.25 h
Max metabolic rate to remain below LOTS with ACES on	≈2000 · BTU h^{-1} (13 min mile)	≈1400 BTU · h^{-1} (fighter pilot)	≈825 BTU · h^{-1} (suit donning assisted)	≈550 BTU · h^{-1} (quiet sitting)	≈400 BTU · h^{-1} (at rest)

CDO = Cognitive Decrement Onset, 99.9–100.9 °F.
LOTS = Loss of Tracking Skills, 100.8–102.6 °F.

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